

## 17. ROCKET ENGINE BIPROPELLANT VALVE PROBLEMS AND CURRENT EFFORTS

by Joseph Fries

NASA Johnson Space Center

### SUMMARY

In developing the highly successful bipropellant valves for the Apollo primary propulsion engines, a variety of developmental problems were encountered and resolved. These problems and the new technology that is being pursued to eliminate or minimize these problems on the Space Shuttle Orbital Maneuvering Engine are discussed. The Space Shuttle, being a reusable system, has new requirements of the valve. The potential effects of these requirements on valve design and potential solutions are also discussed.

### INTRODUCTION

The bipropellant valves, developed for the Apollo primary propulsion engines (Ascent, Descent, and Service Propulsion Systems) were quad-redundant ball valves. The Ascent and Descent engine valves were actuated with fuel and the Service Propulsion System engine valve was pneumatically actuated. The propellants used are earth storable and hypergolic. The fuel, Aerozine 50, is a 50% blend by weight of unsymmetrical dimethylhydrazine and 50% anhydrous hydrazine. The oxidizer is nitrogen tetroxide ( $N_2O_4$ ). Problem areas in these valves included the actuation system, shaft seals, primary seals, filters, position indicators, wiring harness, housing, material incompatibility, lubricants, contamination sensitivity and formation of salts. While these problems were eventually solved and the valves performed well during the Apollo missions, the long life, reusability and maintainability requirements of the Space Shuttle place additional stress on the valves. Several companies are investigating improved valve designs.

## Apollo Valve Development Problems

The Apollo primary propulsion system valves shared many similar development problems. These problems can be categorized into a few broad areas. First, there were the failures due to sliding seals. The sliding seals are in three areas: the ball element seal or primary seal; the shaft seal or secondary seal; and the actuator piston seal.

The primary seal in each of the valves was in contact with the ball at all times; subsequently, when the ball was rotated to open or close the valve, the seal would slide on the ball. The continuous sliding resulted in excessive leakage due to wear of the seal, contamination generated by the wear process, scratching of the seal by deposits on the element, and nipping of the seal as the flow bore passed the seal.

The primary seal on each of the valves was TFE Teflon. The wear of these seals was most evident when the valves were dry cycled. When the valves were cycled dry, the Teflon would abrade and abraded particles would lodge between the ball and the seal. The mechanisms responsible for the wear of the Teflon are not fully understood but it is generally thought that adhesion and freeing of the transferred fragments, either in terms of surface energy or by virtue of fatigue, are of major importance. It is known that when the TFE Teflon is rubbed against other materials, a transfer of layers of materials takes place. It is believed that the wear process involves the laying down and subsequent removal of such transferred layers.

To minimize this problem, the rate at which the valves were dry cycled was reduced. The reduced cycle rate did not eliminate the problem but did minimize it.

Scratching of the seals occurred because of salts forming on the ball element. The salts that formed on the balls were aluminum and ammonium nitrates and were found only in the oxidizer system. Several factors that influence the formation of salts in the oxidizer system are: moisture in the system, where the moisture emanates from both the atmosphere and from the  $N_2O_4$ ; aluminum used in the  $N_2O_4$  system; the absorption and subsequent outgassing of the  $N_2O_4$  from the Teflon seals; and the migration of fuel vapors to the oxidizer system. The scratching of the seal by the salts occurs after the salts form on the ball and the ball is rotated.

Nipping of the primary seals occurred because of sharp edged flow bores and extended lips of the primary seals. This problem was eliminated by redesigning these areas. The redesigns minimized the lip length of the seals and made larger radii on the flow bores.

The shaft seals used in the Apollo primary propulsion system valves were Teflon lip seals and Teflon Omnisseals. In one system the Teflon lip seal was backed by a redundant KEL-F lip seal.

Problems encountered included leakage caused by contamination, incompatible materials, and permeation. A majority of these problems occurred in the  $N_2O_4$  system. In one system contamination was generated by corrosion of an aluminum shaft seal vent line on the  $N_2O_4$  side of the valve. This contamination subsequently damaged the shaft seal. The KEL-F lip seal presented a problem because KEL-F is incompatible with  $N_2O_4$ . The permeation of  $N_2O_4$  through Teflon shaft seals resulted in failure of one of the Apollo valves to actuate due to the reaction with the lubricant in the actuation system drive train and subsequent jamming of the drive train. The permeation occurred during a long term compatibility test and was not considered to be an operational problem.

The actuator piston seals in the Apollo primary propulsion system valves were sliding seals which were a source of problems. One problem was caused by differential expansion between a plastic headed actuator piston and its aluminum housing. This resulted in excessive leakage past the piston. Another problem was the scoring of the actuator piston cavity due to cocking of the piston. In one system, an o-ring intended to be used in a static application was used as the dynamic actuator piston seal. Movement of the piston, for actuation, caused the o-ring to twist. The twisting of the o-ring resulted in excessive checkout fluid (gaseous nitrogen) leakage; however, the actual operating fluid (fuel) did not leak past the seal.

Other categories of development problems encountered were pilot valve leakage, erroneous position switch output, low electrical resistances, sluggish operation, hang-up, filter collapse, and disconnect leakage. A summary of these problems is presented in table 1.

## SPACE SHUTTLE ORBITAL MANEUVERING ENGINE VALVE TECHNOLOGY

### BACKGROUND

The OMS (Orbital Maneuvering System) of the Space Shuttle is similar to the Apollo propulsion systems and will be a pressure fed rocket propulsion system utilizing helium pressurant and nitrogen tetroxide and hydrazine base earth storable propellants. The existing Apollo propellant shutoff valves and actuation systems were designed for single mission usage and, along with less serious deficiencies, are not sufficiently contamination tolerant or propellant compatible to economically and reliably satisfy the Space Shuttle requirements for reusability and extended life.

### REQUIREMENTS

Requirements were established for the valve technology of the OME (orbital maneuvering engine). These requirements are not considered to be firm but are to be used as design goals with emphasis on establishing realistic requirements. Table 2 presents the requirements, or design goals, as defined for the OME valve and actuation system.

The impact of these requirements as related to the long life and reusability of the Space Shuttle is summarized in table 3.

### APPROACH TO ELIMINATE PROBLEMS

From the discussion of the Apollo valve development problems and the potential problem areas imposed by the long life and reusability requirements of the Space Shuttle, a fresh approach must be taken in the OME valve design. Recommended design practices are presented in table 4.

## TECHNOLOGY CONCEPTS

As a result of the current technology efforts, two primary concepts for the OME valve and actuation system have evolved. The first, as shown in figure 1, is referred to as a "moving seat" poppet valve. The actuation system is a brushless direct current motor. In this concept, the valve poppet is stationary. The valve is opened by deflecting the seat. The actuator is located outside of the flow path and connects to the outside of the seat housing. The bellows, as incorporated in the design of this valve, have three purposes. First, to open the valve, they allow the seat to be deflected with respect to the poppet. Second, they provide a hermetic seal between the propellant and actuator. Third, they pressure balance the poppet valve. This minimizes the forces required for actuation.

Key features of this concept are as follows:

1. Streamlined flow path, which is easily decontaminated.
2. Inherent hermetic seal between the actuator mechanism and propellant.
3. Low operating force due to inherent pressure balance, thereby reducing actuation force and power requirements.
4. No sliding parts, so that no wear can occur and no lubrication is necessary.
5. No sliding contact of sealing surfaces.

The electromechanical actuation system eliminates the problems associated with the pneumatic and hydraulic actuation systems used on Apollo by its very nature of being different. However, it is realized that this system will have its own set of problems. It is felt that it is a step in the right direction.

The second concept, as shown in figure 2, is referred to as a "dual" poppet. In this concept the seats are in parallel with respect to flow. The actuation system is also electromechanical. The dual poppet acts to pressure balance the valve, minimizing the actuator force requirements. The only actuation force required is that needed to overcome the spring forces of the axial

guidance flexures and bellows dynamic seal which are sized to provide the necessary sealing closure interface forces. The dual poppet concept has the capability of sealing as reliably as a single poppet valve since the total seal area of a single poppet valve is nearly identical to the combined sealing areas of the dual poppets. Simultaneous sealing of both poppets in the dual poppet concept is assured by making the carrier of one of the seats a spring element. The poppets are fully flexure-guided and the shaft seal features a hydroformed redundant bellows assembly. Thus, frictional forces have been eliminated. Utilization of the dual poppet concept results in a smaller valve envelope because the two poppets are smaller in diameter than a single poppet and the overall diameter of the poppet housing is reduced.

While both of the above described valve concepts would be expected to utilize electromechanical actuation systems, both concepts are capable of being actuated by pneumatics or hydraulics.

#### CONCLUDING REMARKS

The problems encountered in the development of the Apollo primary propulsion system valves were resolved by design modifications, procedural changes, and the relaxation of some requirements resulting from a better understanding of program requirements with time. While this led to highly successful operational valves for Apollo, valve designs must be developed for the Space Shuttle which enhance the life, reusability, and maintainability aspects over those used on Apollo.

TABLE 1  
APS, DPS, AND SPS VALVE FAILURE SUMMARY

FAILURE		TOTAL		
		No.	%	Causes
<b>Total Failures</b>		206	-	-
Sliding Seals	Ball Seal Leakage	109	53%	Contamination, Wear, Scratches, Salting, Corrosion, Teflon Flaking, Galling, Seal Shrinkage
	Piston and Shaft Seal Leakage			
Poppet Seals	Pilot Valve Leakage	26	13%	Contamination, Motion of Solenoid, Assembly Error
	Erroneous Position Switch Output	16	8%	Solder Joints, Environ. Cond., Adjustment Sensitivity
	Low Electrical Resistance	10	5%	Damaged Wire, Faulty Diode, Propellant Fumes, Moisture, Dirt
	Sluggish Operation	8	4%	Unknown Causes
Hang-Up		7	4%	Leaking Oxidizer, Rusted Needle Bearings, Leaking Oxidizer Reacts with Gear Lubricant
Filter Collapse		6	3%	Inadequate Support
Disconnect Leakage		4	2%	Seal Handling Damage
Miscellaneous		20	10%	

TABLE 2  
OME VALVE DESIGN REQUIREMENTS

Parameter	Design Criteria
<u>Compatibility</u>	
1. Fluids	N <sub>2</sub> O <sub>4</sub> , MMH, 50-50 as liquids and vapors; H <sub>2</sub> O at outlets; Freon TF
<u>Performance</u>	
2. Pressures	
Nominal	1413.4 kPa (205 psia N <sub>2</sub> O <sub>4</sub> ) 1434.1 kPa (208 psia MMH)
Operating Range	1185.1 to 1827.1 kPa (172 to 265 psia)
Max Surge	2757.9 kPa (400 psia)
Proof	2757.9 kPa (400 psia)
Burst	4619.5 kPa (670 psia)
3. Flow Rates	5.40 kg/s (11.91 lb/sec N <sub>2</sub> O <sub>4</sub> ) 3.27 kg/s (7.22 lb/sec MMH)
4. Pressure Drop	34.5 kPa (5 psid) max (normal) "balanced" (fail close)
5. Response Time	100 - 1000 ms open 100 - 1000 ms close
6. Response Repeatability	Important
7. Propellant Simultaneity	Design for simultaneous propellant delivery
8. Internal Leakage	10 std cc/hr GHe per seat (0 to 1827.1 kPa (265 psia))
9. External Leakage	1.66 x 10 <sup>-7</sup> std cc/sec GHe per joint
10. Electrical Supply	24 to 30.5 Vdc (27.25 Vdc nom)
11. Electrical Power Limits	To be determined

TABLE 2 (CONT.)

Parameter	Design Criteria
<u>Life</u>	
12. Cycles	4000 wet/pressurized, 6000 dry
13. Missions	100 missions
14. Time	10 years
15. Propellant Throughput	15,526 kg (34,230 pounds per mission)
<u>Environmental</u>	
16. Temperature	
Propellant	4.4°C to 51.7°C (40 to 125°F)
OMS Structure	4.4°C to 48.9°C (40 to 120°F)
Engine Soakback	93.3°C (200°F maximum)
Transport/Storage	-48.3°C to +87.8°C (-55°F to +190°F)
17. Random Vibration	20 to 2000 Hz, 15.3 g rms, 231 hours
18. Shock	1.5 g maximum for 2.60 ms
19. Acceleration	Up to 4 g
<u>Maintainability</u>	
20. General	Easily maintainable
21. Accessibility	To be determined
22. Filter Replacement	To be determined

TABLE 2 (CONT)

Parameters	Design Criteria
<u>Checkout</u>	
23. General	Minimize valve actuations
24. Position Indication	Open and closed positions
<u>Decontamination</u>	
25. General	Easy to decontaminate
26. Fluid	Hot GM <sub>2</sub> purge
<u>Contamination</u>	
27. Self generated	Minimize
28. Propellant	Particle size (microns)      Number of particles      Sample size 0-25                            Not defined 25-50                        1000 part.            500 ml 50-100                       100 part.              sample 100-250                      10 part. 250                            0
29. Filter Rating	Consistent with valve tolerance
<u>Construction</u>	
30. Lubricants	Avoid if possible
31. Dribble Volume	Not critical
32. Failure Position	Close with loss of power
33. Gas Pressure Source	Must be included in valve if used
34. Motors	Brush type not allowed
35. Force Margin	To be determined

TABLE 2 (CONT)

Parameter	Design Criteria
<u>Installation</u>	
36. Envelope	Minimize
37. Mounting Provisions	On side of engine
38. Porting	Parallel or counterflow
39. Port Size	To be determined
<u>Weight</u>	
40. General	Minimize
<u>Duty Cycle</u>	
41. Maximum on-time	870 seconds
42. Actuations per mission	20 maximum

TABLE 3  
POTENTIAL VALVE PROBLEMS  
RELATED TO LONG LIFE AND REUSABILITY OF THE SPACE SHUTTLE

Long Life/Reusability Parameter	OME (Orbital Maneuvering Engine) Potential Valve Problems
<u>High Cycle Life</u> (4000 wet/6000 dry cycles)	Seal deterioration due to wear; seat deterioration due to impact; gear, stop, and bearing failure due to stop impact loads; fluid hammer fatigue failures.
<u>Long Vibration Time</u> (231 hours, 15.3 g rms Vibration)	Fatigue failure of springs and other flexing or rattling elements; seat scuffing; bearing failure; electrical wire and solder joint failures; micro-switch failures; generation of contamination.
<u>Long Life Time</u> (10 years)	Propellant caused corrosion, nitric acid caused corrosion (at $N_2O_4$ valve outlet); limited life materials (elastomers); cold flow, swelling or permanent set of non-metals; decomposition of MMH; propellant reacting with lubricants.

TABLE 3 (CONT)

Long Life/Reusability Parameter	Some Potential Valve Problems
<u>Large Number of Missions</u>	
(100)	Filter clogging or excessive size needed; bellows fatigue due to flow inducing vibration.
<u>Avoidance of Liquid Flushing</u>	
(Use GN <sub>2</sub> Purge)	Inadequate removal of propellants in crevices, seals, or stagnant areas.
<u>Ease of Maintenance</u>	Excessively "high" maintenance level; excessive maintenance time; parts not 100% interchangeable; introduction of contamination.
<u>Ease of Pre-Flight Checkout</u>	Complex checkout requiring long time; inability to isolate fault.

TABLE 4

RECOMMENDED DESIGN PRACTICES TO AVOID OR  
MINIMIZE PAST AND POTENTIAL VALVE PROBLEMS

Past and Potential Valve Problems	Design Approach to Avoid or Minimize
Sliding seal leakage	Avoid sliding seals to minimize wear
Poppet valve leakage	Use elastomer seats for contamination tolerance
Short life of impacting and sliding parts	Reduce inertia; use shock absorbers; avoid sliding fits
Vibration fatigue failures	Replace sensitive mechanical parts with electronics; provide adequate holding forces; design for vibration resistance; design for easy maintenance
Incompatibility with propellants and nitric acid	Use best proven materials; avoid lubricants; design for easy maintenance
Problems with flushing liquids	Design for propellant removal by gas purging (avoid crevices, stagnant areas)

TABLE 4 (CONT)

Past and Potential Valve Problems	Design Approach to Avoid or Minimize
Filter clogging	Design adequate dirt holding capacity; use high micron rating; design for easy maintenance
Field maintenance difficult or impossible	Design for easy maintenance at low level; avoid contamination sensitive construction
Difficult checkout	Design for ease of checkout and isolation of fault to level of maintenance

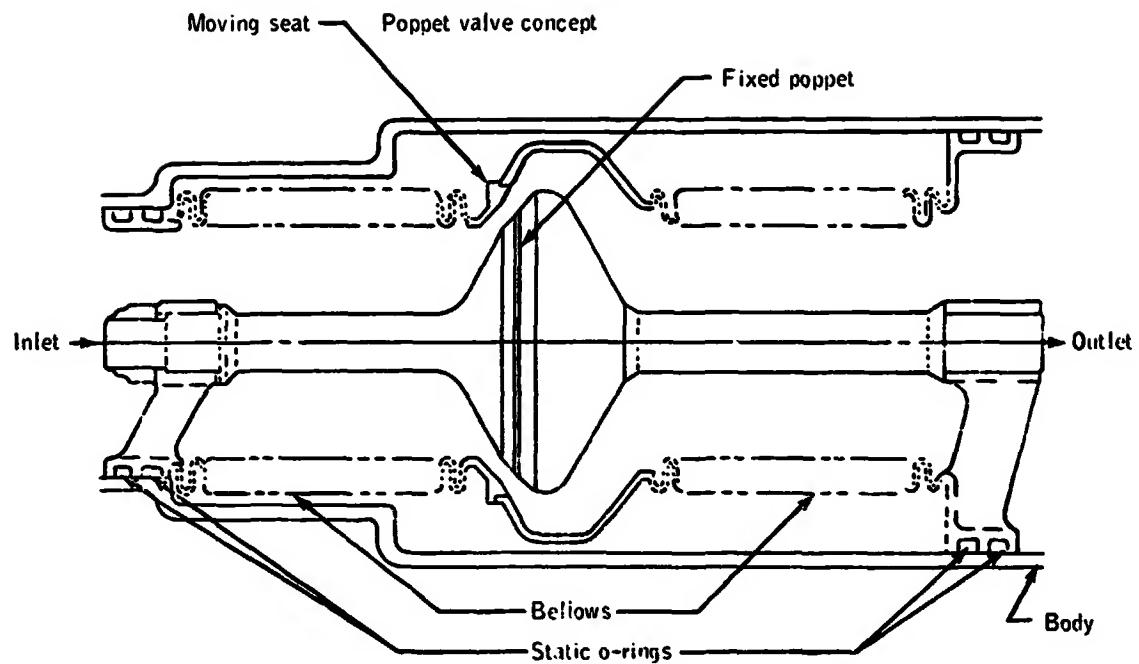


Figure 1.

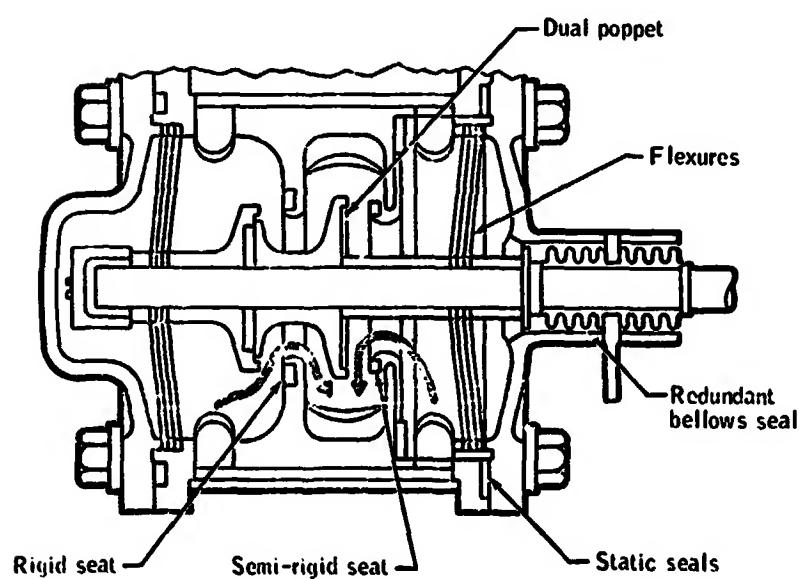


Figure 2.